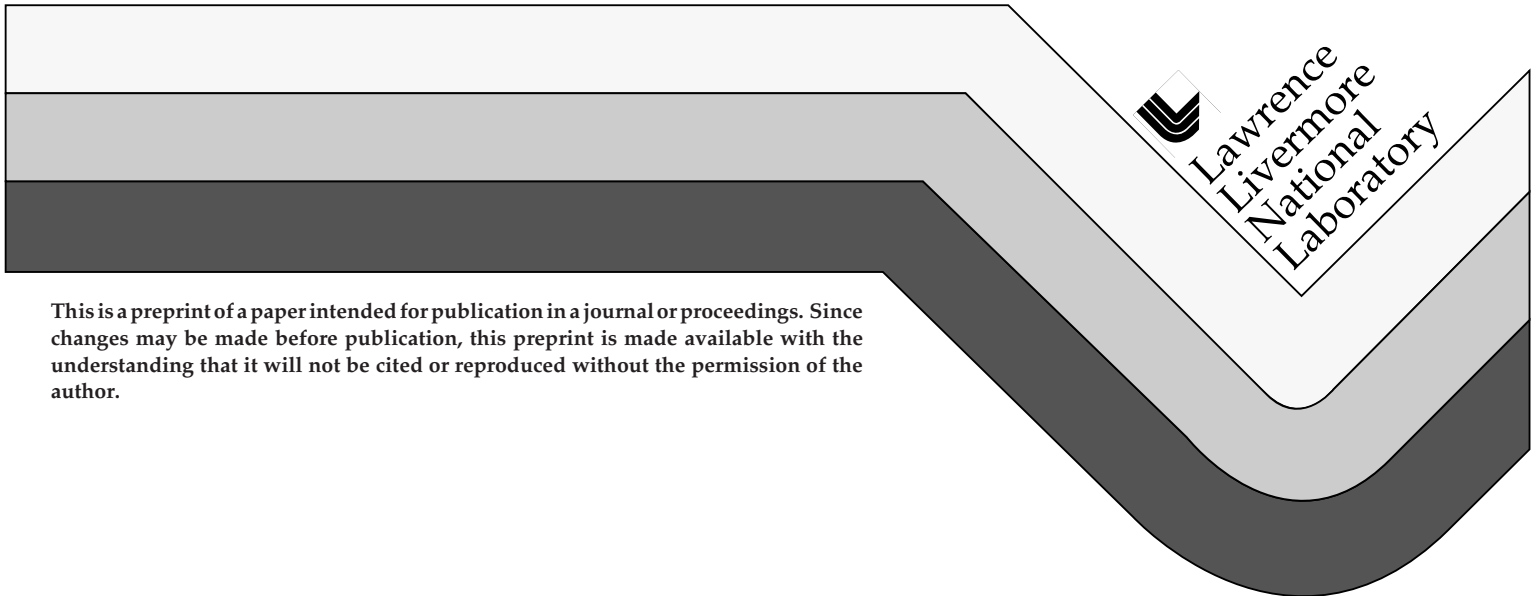


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A FAST RISE-TIME, FIBER OPTIC PIN*

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A reliable, simple fast-rise-time diagnostic has been developed for measuring the breakout time of the detonation wave in a detonating high explosive. The intrinsic rise time of the signals generated is less than one nanosecond. The technique, called FAT (Fiber Arrival Time), consists of an optical fiber with one end coated with $\sim 1500 \text{ \AA}$ Aluminum. The coated end is placed in intimate contact with the surface of the explosive. The detonation wave interacting with the Al surface causes a prompt flash of light which is recorded at the output end of the fiber. The active area of the FAT probe end is $100 \text{ }\mu\text{m}$ in diameter and centered to within $\pm 10 \text{ }\mu\text{m}$ also giving excellent spatial precision. When used in this mode, FAT overcomes difficulties of electronic and past fiber optic pins. When looking at a flyer plate arrival the time response appears to be a function of the metal plate velocity.

INTRODUCTION

Recently, there has been a demand for measurements of detonation wave breakouts with better time resolution than is available with currently existing techniques. Often experimental geometries do not lend themselves to direct optical coupling into detectors. Fiber optic pins are ideal for these situations because the fibers can easily be made to match many geometries. Current fiber optic pins^{1,2}, however, do not have sufficient time resolution for many applications and/or are expensive and complicated to construct. The present technique avoids these problems and has an excellent time response.

DESCRIPTION

The FAT, (Fiber Arrival Time), technique consists of a $100 \text{ }\mu\text{m}$ optical fiber which is Chemical-vapor-deposition (CVD) coated with 1200

- 1500 \AA of aluminum. Other fiber core sizes may be used but the $100 \text{ }\mu\text{m}$ size was chosen to maximize both light collection and time response. The coating thickness is determined by the time response desired and the transmission curve of Al for visible light. The coating must be at least $\sim 500 \text{ \AA}$ thick to avoid the transmission of unwanted light created within the explosive that would be detected before the detonation wave reached the surface of the sample. The choice of 1200 - 1500 \AA arises because the time response is sub-nanosecond and the coating is thick enough to withstand some accidental damage to the integrity of the coating.

The interaction of the detonation wave with the surface of the Al causes an intense, fast rise-time pulse of light that is collected by the fiber and transmitted to an optical detector and recorder. The physical mechanism involved here will be discussed further below. The data discussed in this paper were mainly recorded with an electronic streak camera. The streak camera has the advantage of superior time response and multi-channel recording capability. The output was recorded on film, although a CCD readout could just as easily be employed provided it had adequate spatial and temporal resolution for the desired experiment.

In applications where a streak camera is not necessary or desired one can easily record with a photodiode or photomultiplier tube. Using

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PETN and a 100 μm fiber with 1500 \AA of Al, the signal measured out of a meter of fiber with a calibrated detector is approximately 80 mW, so if a photomultiplier is used attenuation of the signal will be required.

It is very important that the coated fiber surface be in intimate contact with the surface of the HE. Air gaps will seriously degrade the absolute time of the breakout arrival and can cause degradation in the rise time of the signal. Figure 1 shows a simple schematic of the FAT technique.

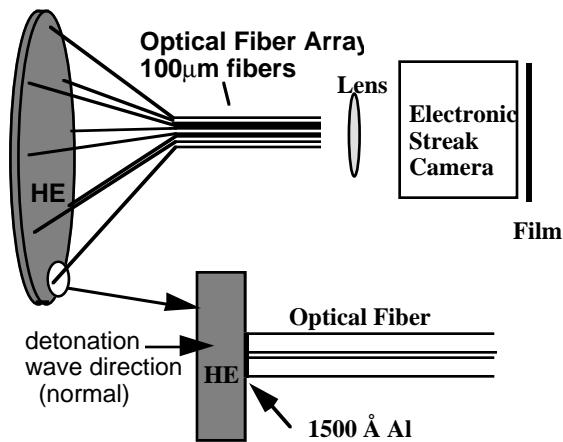


FIGURE 1. SCHEMATIC OF THE FAT DIAGNOSTIC.

EXPERIMENTAL DATA AND USAGE

The FAT technique is extremely useful when the experimental geometry is such that direct optical line of sight collection of the light is difficult or impossible. An example of such a geometry is a circular ring where it is desired to measure the breakout of the detonation wave around the ring. Figure 2 give an example of typical streak camera data from a FAT experiment.

In experiments where the geometry is cooperative one may, of course, directly image an Al-coated piece of glass in contact with the HE surface. The advantage here is that the experimenter gets continuous spatial coverage.

Data have been obtained using this technique on several types of explosives: LX-16 (96% PETN), LX-14 (95.5% HMX), HMX, RDX and RX-08-HD (73.6% HMX, 19.9% TMETN). The ideal geometry of the fiber with respect to the HE surface is such that the the detonation

wave strikes the fiber normal, that is, 90° with respect to the face of the fiber (fig. 1). Most of the data reported had this geometry. Data have, however been successfully taken in the tangential geometry, were the detonation wave is moving parallel to the fiber face. In this case there is a slight degradation in the time response which will depend upon the size of the fiber core used, the detonation velocity of the HE and the angle of the detonation wave with respect to the fiber.

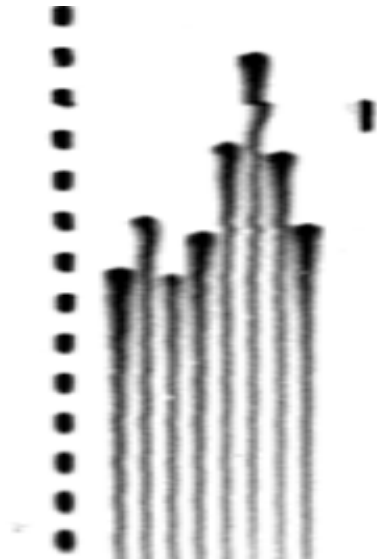


FIGURE 2. STREAK CAMERA DATA FROM A FATS EXPERIMENT. DOTS ON THE LEFT ARE 10 NS APART. THE SINGLE DOT ON THE RIGHT IS A TIMING MARK. THE EIGHT CHANNELS OF FAT DATA ARE IN THE CENTER. TIME FLOWS FROM TOP TO BOTTOM.

The central feature of this technique is the superior time response of the measurement. Figure 3 shows the time response taken using a FAT probe with 1200 \AA Al, a meter fiber length and a sweep window on the streak camera equal to 120 ns. The 10 to 90% risetime of the signal is .68 ns. Breakout times can be determined with even more precision since the breakout signals recorded with this technique are crisp with good signal to noise ratio as can be seen in figure 3.

If the experimenter is forced to use long lengths of fiber (≥ 30 meters) then it may be advisable to introduce a bandpass filter in the line in order to minimize material dispersion in the fiber. The signal emerging from an unfiltered FAT fiber is very broadband (black-body like).

A quick study has been performed to determine if this diagnostic is useful in the case where the experimenter is interested in measuring the arrival time of an explosively-driven flyer plate. In this situation the fiber is separated from the explosive and plate by some distance. Upon detonation arrival at the plate, it is accelerated across the gap and impinges on the Al-coated fiber tip.

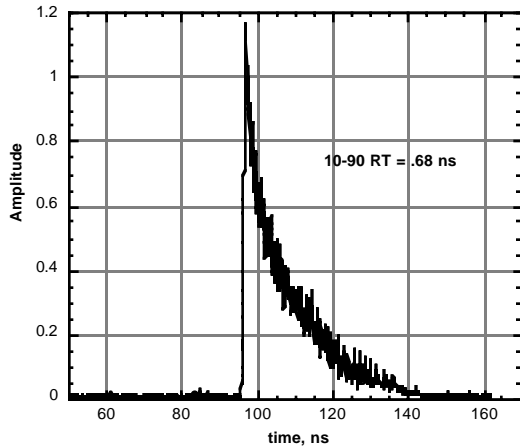


FIGURE 3. TIME RESPONSE MEASUREMENT OF THE FAT DIAGNOSTIC.

Figure 4 gives a plot of the 10- 90% risetimes measured with the FAT diagnostic as a function of the flyer plate velocity. The plot dramatically shows that the time response is degraded for slower velocities. The rough power law fit to this curve is not necessarily correct but serves to illustrate just how sensitive the rise time is to plate velocity.

For measurements where the time response is acceptable for expected flyer plate velocities this technique may work fine. The degradation in time response from the bare He case can probably be understood from the physical mechanism of the light generation which will be discussed in the next section.

SIGNAL GENERATION MECHANISM

In order to better understand the power and the limitations of the FAT technique it would be useful to understand the physical mechanism by which the light signal is generated. Several possibilities come to mind:

- 1) Shock heating of the Al,
- 2) Thermal Diffusivity from the hot high temperature reaction products,
- 3) Al combustion with the reaction products,
- 4) A sudden change in the transmission properties of the Al due to high temperatures and pressure, and,
- 5) A combination of the above effects.

The possibility that the deposited Al films are of less than full density was investigated by measuring the density of the Al films used in FAT. Using Rutherford backscattering measurements combined with a thickness measurement of the Al it was determined that the density of the Al coating was 2.5 gm/cm³. The Al samples are, therefore, 93% of the nominal density for Al of 2.7 gm/cm³. Shock heating at nominal density was calculated to be about 700 K³ and at 93% of full density should not be significantly higher.

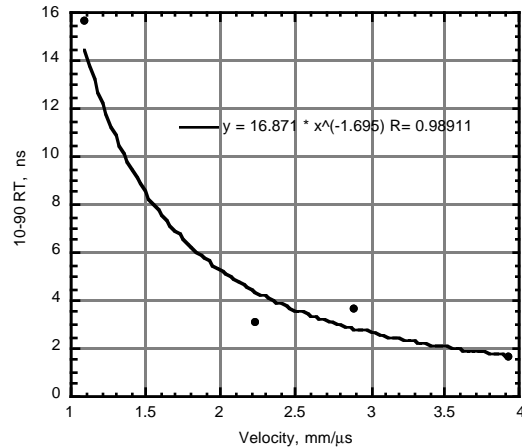


FIGURE 4. 10-90% RISE TIME VARIATION WITH FLYER PLATE VELOCITY.

Another possibility is the hot reaction products in contact with the Al film be cause the back side to heat via thermal diffusivity. A simple estimate for the thermal diffusion time through Al is given by:

$$t = L^2/\pi D$$

- (1) where L = the Al thickness, D= thermal diffusivity, which is given by:

$$D = \text{I}rC_p$$

where l = thermal conductivity, r = density and C_p = heat capacity. Using equation (1) we can estimate that the thermal diffusion time for a 1200 Å thick film of Al is on the order of .17 ns. This time is in good agreement with the rise times observed. However, the timing is not right for thermal diffusion as the sole mechanism behind the signal generation.

Figure 5 shows the signal generated from a much thicker 4.66 µm Al coating compared to the extinction of a laser signal on the back surface of the Al. The onset of the light signal corresponds to within a couple of ns of the extinction of the laser signal. From equation (1) with $L = 4.66$ µm we get a thermal diffusion time of 256 ns. Obviously, this number is far greater than the observation. We thus can conclude that thermal conduction of heat to the output surface of the Al cannot be the main contribution to the signal. In the thickness used in the FAT experiment the conduction mechanism can be a significant contribution to the prompt signal.

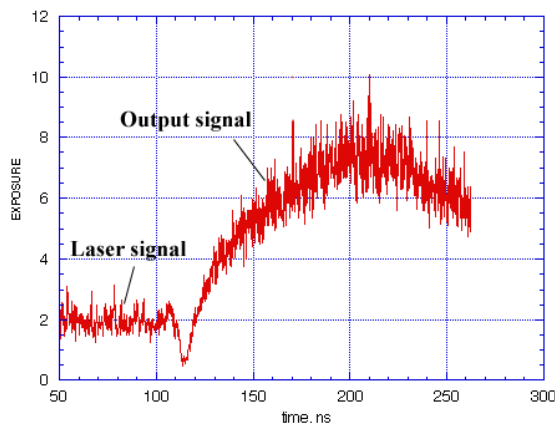


FIGURE 5. COMPARISON OF THE EXTINCTION OF A REFLECTED LASER SIGNAL WITH THE ONSET OF LIGHT FOR A 4.66 µm THICK AL COATING.

Note the much greater rise time for the signal when the Al coating is so thick. This is evidence the coating should be kept in the 1000 Å range.

The possibility that Al combustion is occurring is a good one. Pokhil et al⁴ gives the combustion temperatures of Al to be approximately the melting Al_2O_3 , which is 3800 K at atmospheric pressure. Although the conditions at detonation breakout are certainly not atmospheric pressure, the temperatures are on the order of ≥ 4000 K for PETN, RDX, HMX, and tetryl with TNT falling in the ~ 3500 K range⁵. These temperatures are well above the

temperature necessary for ignition at atmospheric pressure.

In a study for the Navy, the author has observed some evidence for combustion taking place in these thin films of Al. If one observes the light signal omitted as in the FAT diagnostic (only thicker Al samples) compared with the light signal from the surface with no Al coating there is definite evidence of more light, hence more energy created on the Al-coated side. Figure 6 shows an example of the two signals.

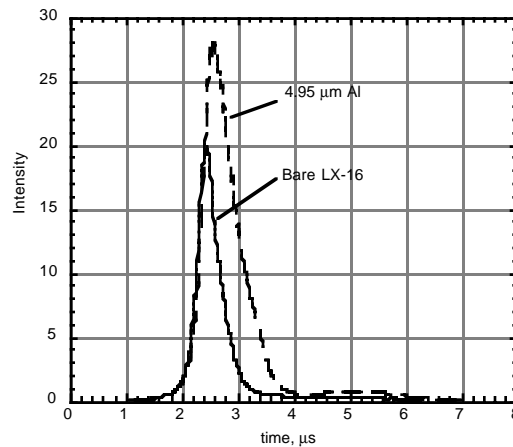


FIGURE 6. COMPARISON OF LIGHT SIGNALS FROM A 4.95 µm AL COATING IN CONTACT WITH LX-16 AND THE UNCOATED LX-16 EMISSION.

Indeed, experiments carried out at Lawrence Livermore National Laboratory have shown that the solid Al casing around an LX-14 charge was completely burned during detonation.⁶

From this, we might conclude that it is highly probable that Al combustion enhances the optical signal observed in the FAT measurement. Al combustion does not, however, likely explain the entire signal.

It is likely that the properties of the Al itself change on the timescale of the signal emission such that the fiber views the hot, combustion products behind the Al film.

There is some peripheral evidence this might be the case in that at static pressures of 310 kbar the reflectivity of Al changes by about 40%⁷. This change in reflectivity can be explained in terms of shifts in the band gap splitting due to pressure. Whether or not band gap changes under the dynamic conditions of a shock

wave pressure and temperature to allow an increase in transmission is much less certain.

A more likely explanation for a sudden change in transmission of the coating is that the coating is physically disintegrating during the time of the pulse. At the pressures created by the detonation wave the shock wave takes only a few tens of picoseconds to traverse the coating. By the time we observe the light pulse reaching full intensity there have been several reverberations and the coating has been put under severe tension by interacting rarefaction waves.

Data taken which may support this theory can be seen in figure 7. The figure displays spectra taken from bare LX-16 compared to the same LX-16 seen through 1500 Å of Al. In both cases the data was taken through a 100 µm diameter fiber. The data is corrected for the streak spectrometer response. The data does not fit very well to any graybody curve. A 4200 K graybody curve is shown on the graph as a reference point to what might be the best match.

The data suggests that what we might be seeing here is a graybody output with a multitude of broadened lines riding on top of the curve. We might expect line outputs from the detonation products such as C₂, CO, O₂⁺, CO⁺, OH, H and CO₂ in the case of bare LX-16 and we expect to see an additional signal from AlO bands in the case of the Al coated sample.

The main point to note here, however, is that the spectrum looking through the Al coating is to first order very similar to the bare HE spectrum. The overall increase in the intensity of the Al-coated spectrum could arise from additional energy due to combustion of the Al. Another possible explanation is that this particular measurement was dominated by hotspot emission⁸ which we are

FIGURE 7. COMPARISON OF THE SPECTRA OF DETONATING LX-16 WITH LX-16 SEEN THROUGH A 1500 Å AL COATING.

seeing in transmission. Subtle differences in the structure of the curves could arise from the introduction of Al lines in the case of the Al-coated spectrum.

In any case, the spectra are similar enough to suggest that the light output from the Al-coated case arises from the transmission of the signal from the hot detonation products on the HE as the Al barrier becomes transparent. The data also suggest support for the supposition that Al combustion may be enhancing the signal to some degree.

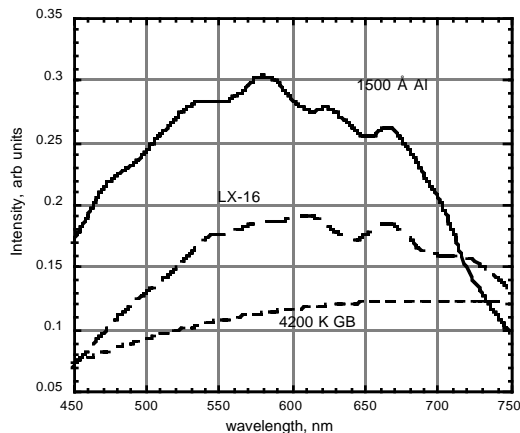
SUMMARY AND CONCLUSIONS

The FAT diagnostic technique has been shown to be a highly useful, inexpensive, simple way to measure arrival times of detonation waves at the surface of detonating high explosives. The method has a sub-nanosecond time response and allows the experimenter to obtain excellent cross-channel timing. The technique is especially useful in geometries that do not lend themselves to direct optical imaging of the data.

The FAT technique may also be useful measuring the arrival times of explosively-driven flyers. In this case the response time of the FAT signal depends upon the flyer velocity so the experimenter must decide if the expected time resolution of the diagnostic is sufficient for the measurement.

The most probable explanation as to the cause of the optical signal observed in the FAT diagnostic is that the thin Al coating is changing its transmission as the detonation wave impinges upon it, allowing the fiber to collect light from the hot detonation products behind the Al layer. For the thickness of films used in the FAT diagnostic, thermal diffusivity and Al combustion may also be contributing to the signal. This explanation is also consistent with the results on explosive driven flyers. In this case the signal is likely to have been generated in the hot, shock-compressed air between the flyer and the Al coating. Higher velocity flyers would cause a faster temperature rise in the compressed region that slower moving flyers, hence, giving slower response times for slower flyers.

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